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EFFECT OF REDUCED AMBIENT PRESSURE ON THE HOT WIRE SENSITIVITY OF PRIMARY EXPLOSIVES, METAL-OXIDANT MIXTURES, AND BLACK POWDER

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EFFECT OF REDUCED AMBIENT PRESSURE ON THE HOT WIRE SENSITIVITY OF PRIMARY EXPLOSIVES, METAL-OXIDANT MIXTURES, AND BLACK POWDER

Howard S. Leopold

ABSTRACT: The hot wire sensitivity of initiating materials can change under vacuum conditions. Lead azide, silver azide, black powder, and mixtures of $Zr/KClO_4$ require slightly more energy for initiation under vacuum conditions. Basic lead styphnate and normal lead styphnate require slightly less energy for initiation under vacuum conditions. The loading density affects the energy differential. Hypotheses are proposed for the observed energy changes.

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U. S. NAVAL ORDNANCE LABORATORY
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EFFECT OF REDUCED AMBIENT PRESSURE ON THE HOT WIRE SENSITIVITY OF PRIMARY EXPLOSIVES, METAL-OXIDANT MIXTURES, AND BLACK POWDER

This report describes the results of an investigation on the effect of vacuum on the hot wire initiation of various initiating materials. The investigation was performed under Task ORD 332-003/092-1/UF17-354-302, Explosives Development.

The results should be of interest to personnel engaged in initiation research and in the design of electric initiators and power supplies therefor.

E. F. SCHREITER
Captain, USN
Commander

C. J. Aronson

C. J. ARONSON
By direction

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INTRODUCTION

In order to increase the reliability of explosive trains, the initiation process and the growth of explosion must be thoroughly understood. Many factors affecting the initiation of explosives in initial explosive components have still not been explained. Further, study of these factors. both chemical and physical, is needed in order to build safe, reliable, and effective fuze trains.

The high altitude use of electroexplosive devices (EED's) in the POLARIS and other missiles and the increasing amount of vacuum chamber experiments have created another pressure environment for Navy EED's. Previously, EED's were designed to function at sea level atmospheric pressure or the higher pressures of various ocean depths. To overcome any possible low pressure effects, hermetically sealed EED's are usually employed so that the hot wire/explosive interface is not exposed to the reduced pressure. The possibility of air leakage out of defective hermetically sealed devices and reports of both decreased and increased EED sensitivity under vacuum conditions made it advisable to examine in greater detail the effect of reduced pressure on the hot wire sensitivity of initiating materials.

EXPERIMENTAL

The explosive material under test was loaded into an aluminum charge holder force fitted onto a standard two-pin phenolic initiator plug. The initiator plug had been previously bridged with a 1-mil diameter nichrome wire. See Fig. 1.

The loaded initiator plug was mounted in a test chamber as shown in Fig 2 and the test chamber was pumped down to the desired vacuum of 5-15 microns by a two-stage vacuum pump. A McLeod gauge was used to measure the pressure. The pressure test range used corresponds to an altitude of 80,000 meters or 260,000 ft. See Fig 3. The pump down of the test chamber and the measurement of the pressure usually required 3 to 5 minutes. The explosive or pyrotechnic was exposed to the chamber conditions for only this length of time. The test chamber was fitted with a transparent plastic window so that upon firing the intensity of the explosive flash could be observed.

Bruceton tests were used to determine the mean firing energy[1]*. When paired Bruceton tests were run, such as a comparison of the explosive hot wire sensitivity under ambient and vacuum conditions at the same loading pressure, the tests were made by first firing 10 shots under vacuum conditions and then 10 shots under ambient conditions with the procedure repeated until the two Bruceton tests were completed.

*References are on page 11

EXPERIMENTAL RESULTS

Zirconium/Potassium Perchlorate Mixtures

To test the effect of vacuum on the hot wire sensitivity of fuel/oxidizer mixtures $Zr/KClO_4$ was used. This mixture is typical of mixtures being used by commercial producers to obtain 1-amp/1-watt no fire electroexplosive devices. Zirconium in subsieve sizes is an easily ignited fuel. In this fine size it will ignite at a temperature of 180°-200°C in air[8]. Larger size zirconium particles will generally require higher temperatures. Potassium perchlorate shows incipient decomposition at 400°C, melts at 588°C, and decomposes rapidly above 600°C[8]. Ellern has reported that in pairing an active fuel with an inactive oxidizer, the fuel determines essentially the ignition point[8]. The energy required for hot wire ignition of Zr/oxidizer mixtures has been found to be relatively independent of the type of oxidizer, agreeing with Ellern's statement[8].

Five $Zr/KClO_4$ compositions ranging from fuel poor (1/3 and 2/3 amount of stoichiometric fuel), to stoichiometric (chemically balanced), to fuel rich ($1\frac{1}{3}$ and $1\frac{2}{3}$ amount of stoichiometric fuel) were prepared by dry tumbling Zr (JAN-A-399A, 3±1 micron average diameter) and $KClO_4$ (<44 microns). These mixes were pressed into the charge holders at 10,000 psi, a commonly used loading pressure. Fifty shot Bruceton tests were run to determine the mean firing energy and dispersion under both ambient and vacuum conditions. The results are shown in Fig 4.

In general, more energy is required for ignition under vacuum than under atmospheric conditions, with the least amount of additional energy required with the stoichiometric composition. Mixtures differing the most from stoichiometric require more energy for ignition under both vacuum and atmospheric conditions. It is believed that the higher energy needed for the ignition of the $1\frac{2}{3}$ fuel rich mixture is due to the higher concentration of zirconium which rapidly conducts heat away from the wire/mixture interface. The heat is dissipated throughout a larger mass of the mixture, thereby requiring greater energy input to reach the ignition temperature. On the extreme fuel poor side, the volume of fuel (zirconium) in the mixture is now fairly low (ca. 15%) and is more difficult to ignite. The dispersion of the energy required for igniting the mixtures is much higher than the dispersion for single primary explosives. The 1/3 fuel poor mixture had very poor pressing properties and an extremely large energy dispersion, probably due to movement of the mixture when exposed to vacuum. The other mixtures had good pressing properties and they stayed intact under the test conditions.

Primary Explosives

Fifty shot Bruceton tests were used to investigate the hot wire sensitivity under both atmospheric and vacuum conditions of five different primary explosives:

milled basic lead styphnate (BLS)
milled normal lead styphnate (NLS)
silver azide and milled dextrinated lead azide
milled lead mononitroresorcinate (LMNR)

The explosives were loaded at 10,000 psi. Bruceton testing with the LMNR was discontinued after firing a few shots as the results were difficult to interpret. Firings conducted at the 50% firing energy region under ambient conditions would not result in the entire combustion of the LMNR in the charge holder. A typical result appears to be a hemicylindrical burnout of half the cross sectional area of the cylindrically shaped pressing in the charge holder. See figure 5. Expulsion of unburnt LMNR from the charge holder was also observed. Firings under vacuum conditions with LMNR were not attempted. The results with the other four explosives are shown in figure 6. Both styphnate explosives appear to require less energy under vacuum conditions, while both azides appear to require more energy under vacuum conditions.

Additional Bruceton tests were run at different loading pressures to further examine the sensitivity changes. Dextrinated lead azide and basic lead styphnate were used for the additional tests since these two explosives exhibited the largest sensitivity change of each type of explosive.

Basic Lead Styphnate

Further Bruceton testing was conducted with BLS to investigate the increased sensitivity. See figure 7. The sensitivity of the BLS remains fairly constant under atmospheric conditions as the loading pressure is varied.* Under vacuum conditions, the decrease in initiation energy is greatest at the lower loading pressures where the most voids are present. The sensitization effect disappears at the high loading pressure with approximately the same amount of energy required as under atmospheric conditions.

Lead Azide

Bruceton tests were conducted with milled dextrinated lead azide over the same loading range as used for the BLS. See figure 8. Less initiation energy is required as the loading pressure is increased. Stresau and Rowe have reported this effect for PVA, Service, and dextrinated lead azide and also for silver azide.[4] See figure 9. Under vacuum conditions, the same decrease in initiation energy is observed as the loading pressure is increased. The extra initiation energy required under vacuum conditions diminishes as the loading pressure is increased.

*Previous unpublished experiments with NLS have shown the same effect.

Black Powder

Black powder is occasionally used as an initiating agent. It requires much higher initiation energies than needed for the commonly used primary explosives. Bruceton-type and probit type tests were run under vacuum and ambient conditions with black powder meal (finest granulation available) loaded directly on the bridgewire. See figure 10. Less initiation energy is required as the loading pressure is increased. Under atmospheric conditions, the energy dispersion is quite high and a forceful ejection of red sparks is observed when firings occur. When fired under vacuum conditions, more energy is required for initiation, the energy dispersion decreases considerably, and the combustion is weaker appearing as a blue flame. A blue flame was considered the criterion for a fire under vacuum conditions. Partial fires under vacuum conditions were also observed; characteristics were a faint red glow and ejection of the black powder meal from the initiator plug with the plug retaining a burnt smell. No visual difference in output was detected over the experimental loading range. At the energy levels employed for the initiation of black powder, the bridgewire does not remain intact, but bursts into molten particles or explodes depending upon the amount of energy used.

STATISTICAL CONSIDERATIONS

It is a matter of judgement as to what percent level of significance is used when comparing the results of experiments. For many purposes the 5% level is accepted. This means that 1 in every 20 times an effect is asserted to exist, it really does not. The 50% firing points observed in these experiments are not statistically significant at the 5% level using the significance test in AMP Report No. 101.1R.[1] This does not mean that the effect does not exist, but may be obscured by possible errors of estimates from samples. In some cases, differences can become significant as the sample is enlarged. It was calculated using the Bruceton significance test that increasing the sample size to 1000 or even 5000 samples (prohibitive amounts for normal testing) over the 50 sample Bruceton tests actually run would fail to make the results significant at the 5% level.

Using the null hypothesis approach, if there were no difference in initiation energy for NLS between air and vacuum, by pure chance a series of paired Bruceton tests should result in the lower energy Bruceton test appearing half the time in the vacuum Bruceton and half the time in the air Bruceton. A review of unpublished data by C. Dieter shows 11 consectutive paired Bruceton tests run with NLS to give a lower energy requirement under vacuum conditions. See table 1. By pure chance, the odds of this run occurring if no difference existed are $\frac{1}{2^{11}}$ or one chance out of two thousand forty eight. A run of 5 straight $(\frac{1}{2^5})$ or one chance out of thirty two would make the results significant at the 5% level. Thus, though the energy difference between the means of each test pair is not statistically significant, a high level of significance can be shown when a series

of Bruceton tests are run. The current tests with BLS and NLS confirm the previous data. Even though a series of Bruceton tests to make the results significant were not run with lead azide, it is believed that the observed differences are as real as those observed with the styphnates. This belief is strengthened by the observed consistency of an expected trend (decrease in energy difference between vacuum and air as explosive density increases). The same type of consideration also applies to the $Zr/KClO_4$ mixtures and the black powder meal.

DISCUSSION

$Zr/KClO_4$ Mixtures

It is believed that when $Zr/KClO_4$ mixtures are fired under ambient conditions, the Zr can initially react with the interstitial air in the voids of the mix. A possible explanation for the greater energy requirement under vacuum conditions where the interstitial air is not present is that additional energy is required to decompose the $KClO_4$ so that it can furnish the necessary oxygen for ignition. The results are indicative only of the energy required for ignition and not indicative of the strength of the ensuing propagation which appears to be much weaker under vacuum conditions. Russian investigators have found the ignition of stoichiometric $Zr/KClO_4$ pellets under vacuum conditions results in the reaction of only 10% of the Zr.[5]

Extreme care should be taken if extrapolations are made from these test results to other fuel/oxidizer combinations. The reported results are for short term exposure to vacuum. If the vapor pressures of the mixture constituents differ widely, long term exposure to vacuum could result in drastic compositional changes. The results reported should be typical of an active metal fuel paired with a fairly inactive oxidizer. If the fuel is a poor conductor instead of a metal, an energy increase under vacuum conditions may not be observed.* If there is specific interest in the use of an active metal/oxidizer composition under vacuum conditions, various loading pressures should be investigated to determine if a loading pressure effect exists also.

BLS

The following hypothesis is offered as an explanation for the decreased ignition energy of BLS under vacuum conditions when abundant voids are present. The bridgewire when heated under ambient conditions can transfer heat to the initiator plug, explosive particles, and interstitial air. Under vacuum conditions, heat can only be transferred to the initiator plug and explosive, since a vacuum cannot conduct heat. This results in greater heat transfer efficiency to the explosive. Since the difference between ambient and vacuum can be readily observed with Bruceton testing, it

*See BLS discussion.

appears that air can remove a portion of the heat from the bridgewire which is not utilized in the explosive ignition.

Support for the above hypothesis lies in the observation that even though air has approximately only 1/1000 the heat capacity of the explosive, there is what is called a heat diffusibility factor. That is, the air has movement and can transfer heat over a much greater distance from the bridgewire than the fixed explosive. For example, the thermal conductivity of crushed basalt has been found to be 100 times lower in vacuum than when measured in air at atmospheric pressure.[8] No handbook values could be found for the thermal conductivity of BLS, but that of lead azide is given as only 2.7 times greater than that of air. Experiments with the Mk 1 Squib have shown that the heat capacity of the bridgewire system (C_p) when surrounded by explosive is only 1.7 times greater than when surrounded by air.[7] The heat loss factor (γ) for explosives in the same experiments with the Mk 1 Squib is approximately 4 times that of air.[7] These figures indicate that air can exert a considerable influence on the heat capacity and heat loss of a bridgewire system when the explosive is a fairly poor conductor. It is believed that this effect was not observed with the $Zr/KClO_4$ mixtures because the thermal conductivity of Zr is approximately 1000 times greater than that of air, making any heat transfer through air negligible in comparison.

To partially confirm the hypothesis, further Bruceton tests were run with BLS in an atmosphere of helium which has a lower heat capacity than does air and in an atmosphere of sulfur hexafluoride which has a higher heat capacity than does air.

Gas	Heat Capacity (STP)
Helium	0.21×10^{-3} cal/cm^3
Air	0.35×10^{-3} cal/cm^3
Sulfur Hexafluoride	1.03×10^{-3} cal/cm^3

The BLS was loaded in the initiator plug at 10,000 psi. The test results are shown in Table 2. The 50% firing energy appears to vary with the heat capacity of the gas. E. Jones has shown that as the excitation time approaches zero, the quantity of heat absorbed presumably varies with the thermal capacity of the gas (if the gas is thermally stable).[8] With longer excitation times, the diffusibility of the gas becomes more important and the heat loss should vary with the thermal conductivity of the gas. The results though admittedly not statistically significant, support the original premise.

Lead Azide

Lead azide, though also a fairly poor conductor, exhibits an opposite effect from the styphnates in that it requires more energy under vacuum than under ambient conditions. It appears that whatever the operative mechanism, it is strong enough to outweigh

the air heat loss factor. Possible explanations for the greater amount of energy required were then investigated.

1) Absence of air or oxygen - Lead azide is considered to be an oxygen negative explosive if the lead is to be oxidized and may possibly require more energy under vacuum conditions. There is also a possibility that one of the constituent gases of air catalyzes the decomposition reaction. These possibilities, however, appear improbable since lead azide has been observed to become more hot wire sensitive at higher loading densities where less available air is present.

2) Evaporation of Sensitizing Volatile Component - There is the possibility that when the milled dextrinated lead azide loaded plugs are exposed to vacuum, a volatile sensitizing component is lost, necessitating higher initiation energies under vacuum conditions. To examine this possibility, loaded lead azide plugs were exposed to vacuum for ten minutes. A Bruceton test was then run with these plugs under ambient conditions. The resulting Bruceton energy mean was almost the same as for the control groups of initiator plugs which had not been pre-exposed to vacuum. See figure 8. This eliminated the possibility of the loss of a sensitizing volatile component as an explanation for the increased initiation energy required under vacuum conditions.

3) Permanent Sensitization - Another mechanism which might account for the results observed with lead azide is the permanent sensitization or so called "memory" property of lead azide. Ubbelohde has shown that if there is an induction period of 10 seconds for lead azide to explode at a certain temperature, the lead azide can be held at that temperature for 5 seconds, cooled to room temperature, held for a period of time, and when reheated to the same temperature will require approximately only 5 seconds until explosion occurs.[9] In other words, the lead azide "remembers" that it had previously absorbed a certain quantity of energy. The same property has also been demonstrated by various other experiments such as a decrease in the required drop height for 50% firing after exposure to intense light or heat.

The relationship of the permanent sensitization phenomenon to the test results observed might be, that as higher loading pressures are employed, strains are produced in the lead azide crystals, making them more sensitive at higher loading pressures.* When the initiator plugs are exposed to a vacuum, some of the crystal strain could be released, causing desensitization, and thereby accounting for the greater energy required under vacuum conditions. This possibility was investigated in the following manner. Lead azide crystals were exposed to 30,000 psi air pressure for a few minutes and then loaded into the initiator plugs at 10,000 psi. A Bruceton test was run under ambient conditions and the result is shown in figure 8. Though not statistically conclusive, the test indicates

*NavOrd 4197 tells of decreased impact sensitivity with strain relief in azide crystals.

that perhaps some sensitization can occur. However, if the test is compared to the results obtained with the 30,000 psi loading, it can be seen that the observed energy decrease is not sufficient to account for the entire energy decrease observed with the 30,000 psi loading. Also, if the Bruceton test run on the plugs pre-exposed to vacuum before firing at ambient conditions is re-examined, it can be seen that exposure to vacuum produced no desensitization. It therefore appears that the permanent sensitization property of lead azide cannot account for all of the large increase in sensitivity with higher loading pressures or the decreased sensitivity under vacuum conditions.

The following hypothesis is proposed as a common explanation to account for the dual phenomena of both increased hot wire sensitivity at higher densities and the decreased hot wire sensitivity under vacuum conditions. It is an extension of Yoffe's explanation for the decomposition of liquid azides under vacuum conditions.[10] In lead azide the burning stage is absent with detonation commencing almost immediately. If the decomposition of lead azide is examined on an expanded time scale before detonation commences, the following phenomena occur:

1) Heat from the hot wire raises azide electrons to a conduction band

$$N_3^- \rightarrow N_3 + e$$

2) These electrons combine with lead ions to form lead nuclei

$$Pb^{++} + 2e \rightarrow Pb$$

3) The azide radicals form nitrogen molecules in an exothermic reaction (11)

$$2N_3 \rightarrow 3N_2 + 232 \text{ K cal}$$

The nitrogen molecules formed are quite hot and energetic. It is believed at the lower loading densities where the interstitial spaces are quite numerous, these hot molecules can rapidly move away from their origin at the wire/lead azide interface. As the density of the lead azide is increased and the interstitial spaces and paths become less numerous, the diffusion of the hot molecules is hindered. The extreme case might be a small closed air pocket, where the hot wire in addition to heating adjoining lead azide crystals, also heats the air, creating a slight pressure rise which tends to momentarily retain the nitrogen molecules close to the crystal surface. It is believed that the reason more energy is required for initiation under vacuum conditions is that there are no gaseous molecules to restrict the movement of newly formed nitrogen molecules away from their formation sites. Hence more energy is required to produce a faster initial decomposition so that sufficient nitrogen molecules will remain in situ to accelerate the decomposition. It appears that though the primary mechanism for initiation of the azides is thermal,

there is a very definite secondary gaseous effect. This effect manifests itself in the increased sensitivity at higher loading pressures and in the decreased sensitivity under vacuum conditions.

Black Powder Meal

The initiation of a 3 component mixture such as black powder (KNO_3, C, S,) is considerably more complicated than a single explosive. Though the actual mechanism of initiation and burning is still obscure, the main functions of each component are known. The KNO_3 is the oxygen producer and the C is the main combustible material. The S makes the powder more readily inflammable and forms K-S complexes, preventing part of the CO_2 evolved from forming potassium carbonate and thereby reducing the amount of gas evolved.

It is well known that the burning rate of black powder is pressure dependent and the performance below one atmosphere pressure is poor, i.e., decreased light output and considerable unburnt residue are observed.[12] "It has also been observed that increasing pressure lowers the delay to ignition by a hot wire."[12]

It is interesting to compare the increased sensitivity of black powder as the loading pressure is increased to that of the azides for which a pressure dependent initiation has also been postulated. More energy is required under vacuum conditions for black powder and lead azide as would be expected for a pressure dependent initiation. However, there is a difference between the black powder and lead azide in that the vacuum and ambient initiation energies of le azide tend to converge as would be expected with higher loading pressures while those of black powder tend to diverge. It appears that the initiation energy curves obtained for black powder under ambient and vacuum condition should not be compared too closely since different reactions occur under each condition. The red sparks observed under ambient conditions are typical of a carbon combustion with all 3 components reacting, while the blue flame observed under vacuum conditions is probably indicative of a dominating KNO_3 reaction with the more inflammable S.

CONCLUSIONS

The conclusions reported are for short term (<5 minutes) exposure to vacuum.

1. $Zr/KClO_4$ mixtures require more energy for hot wire ignition under vacuum conditions. The reaction is much weaker under vacuum conditions.

2. BLS and NLS require less energy for hot wire initiation under vacuum conditions.

3. Lead azide and silver azide require more energy for hot wire initiation under vacuum conditions.

4. The initiation energy differential between vacuum and air for styphnates and azides decreases with increasing density.

5. The energy differential at a 10,000 psi loading pressure (prevalent value used in hardware) between air and vacuum will not be drastic (<10%).

6. An increased thermal transfer efficiency is postulated for the energy decrease in the hot wire initiation of styphnates under vacuum conditions.

7. Greater retention of energetic nitrogen molecules is postulated to be responsible for the increased hot wire sensitivity of azides at high densities. Rapid escape of energetic nitrogen molecules is postulated to be responsible for the decreased sensitivity under vacuum conditions.

8. Black powder meal requires less energy for initiation as the density is increased.

9. Black powder requires more energy for initiation under vacuum conditions. The reaction is much weaker under vacuum conditions.

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TABLE 1

Bruceton Test Results for Normal Lead Styphnate
at Ambient and Reduced Pressure*

Test No.	Bridgewire		50% Firing Energy (ergs)	
	Diameter	Material	760 mm	0.3-0.5 mm
1	1 mil	Nichrome	44,870	38,280
2	1 mil	Tungsten	32,150	30,200
3	0.4 mil	Nichrome	7,940	6,400
4	0.4 mil	Nichrome	2,280	2,050
5	1 mil	Nichrome	7,530	7,160
6	0.4 mil	Tungsten	2,150	2,080
7	1 mil	Tungsten	6,340	5,850
8	0.4 mil	Nichrome	8,040	6,880
9	1 mil	Nichrome	39,500	31,900
10	0.4 mil	Tungsten	5,430	4,960
11	1 mil	Tungsten	32,100	30,200

*From unpublished data by C. Dieter

TABLE 2

Effect of Atmosphere on 50% Firing Energy of
Basic Lead Styphnate

Atmosphere	50% Firing Energy (ergs)	Sigma (log units)
Vacuum	13,310	0.019
Helium	14,370	0.035
Air	14,580	0.013
Sulfur Hexafluoride	14,910	0.016

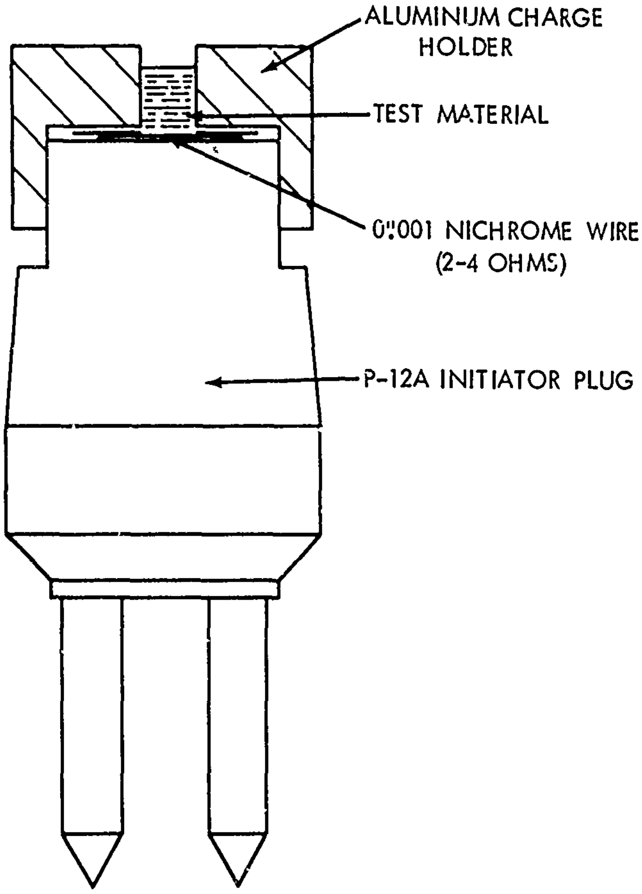

FIG. 1 INITIATOR PLUG ARRANGEMENT

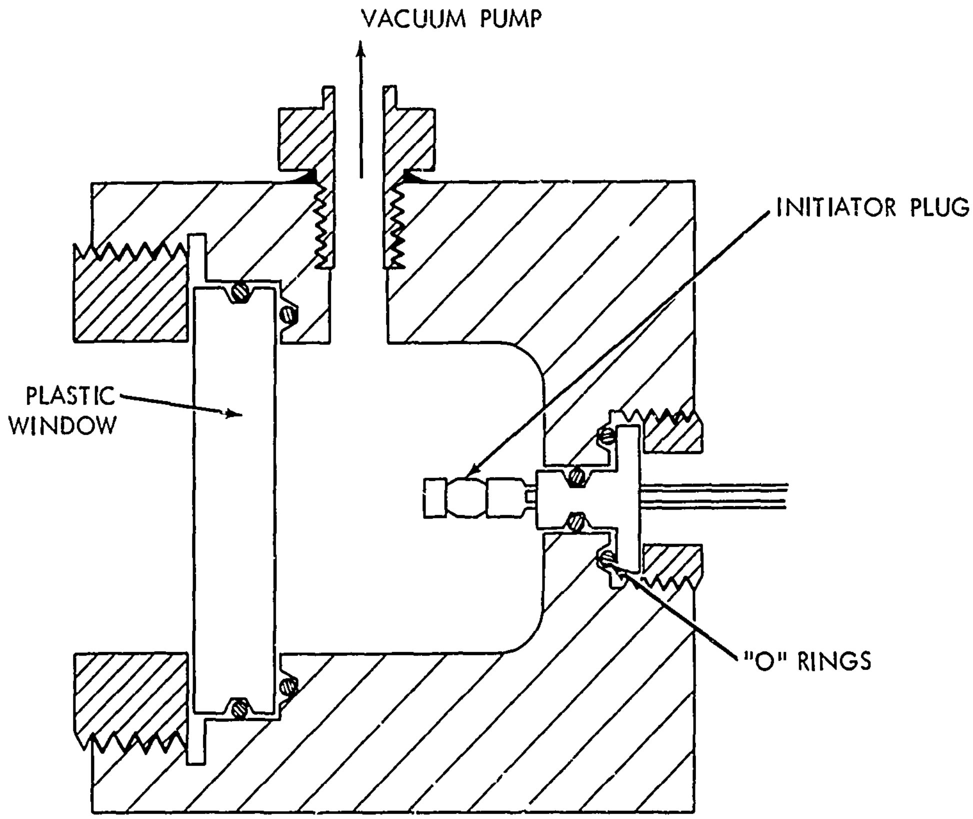

FIG. 2 TEST CHAMBER

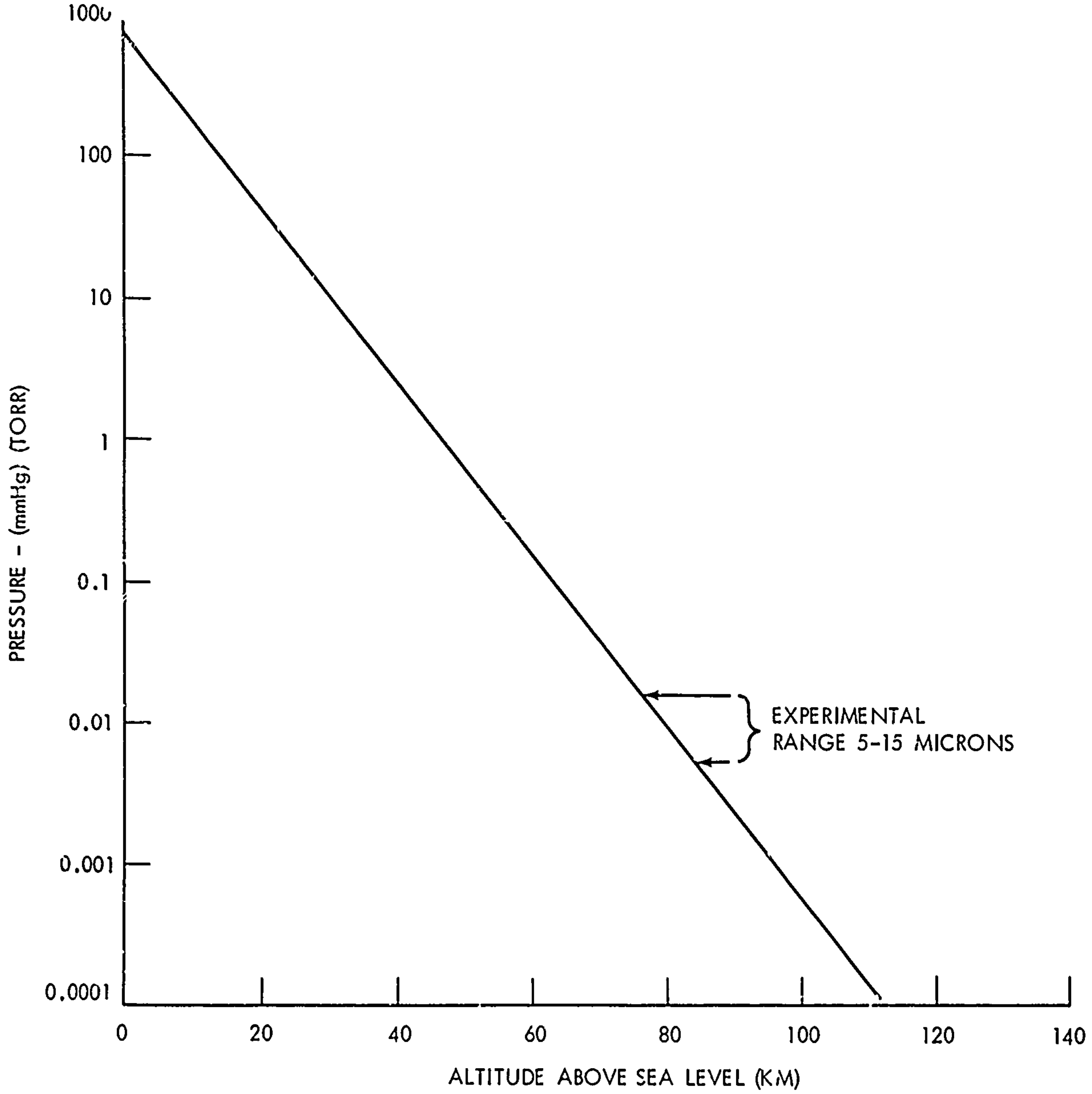

FIG. 3 PRESSURE VS. ALTITUDE

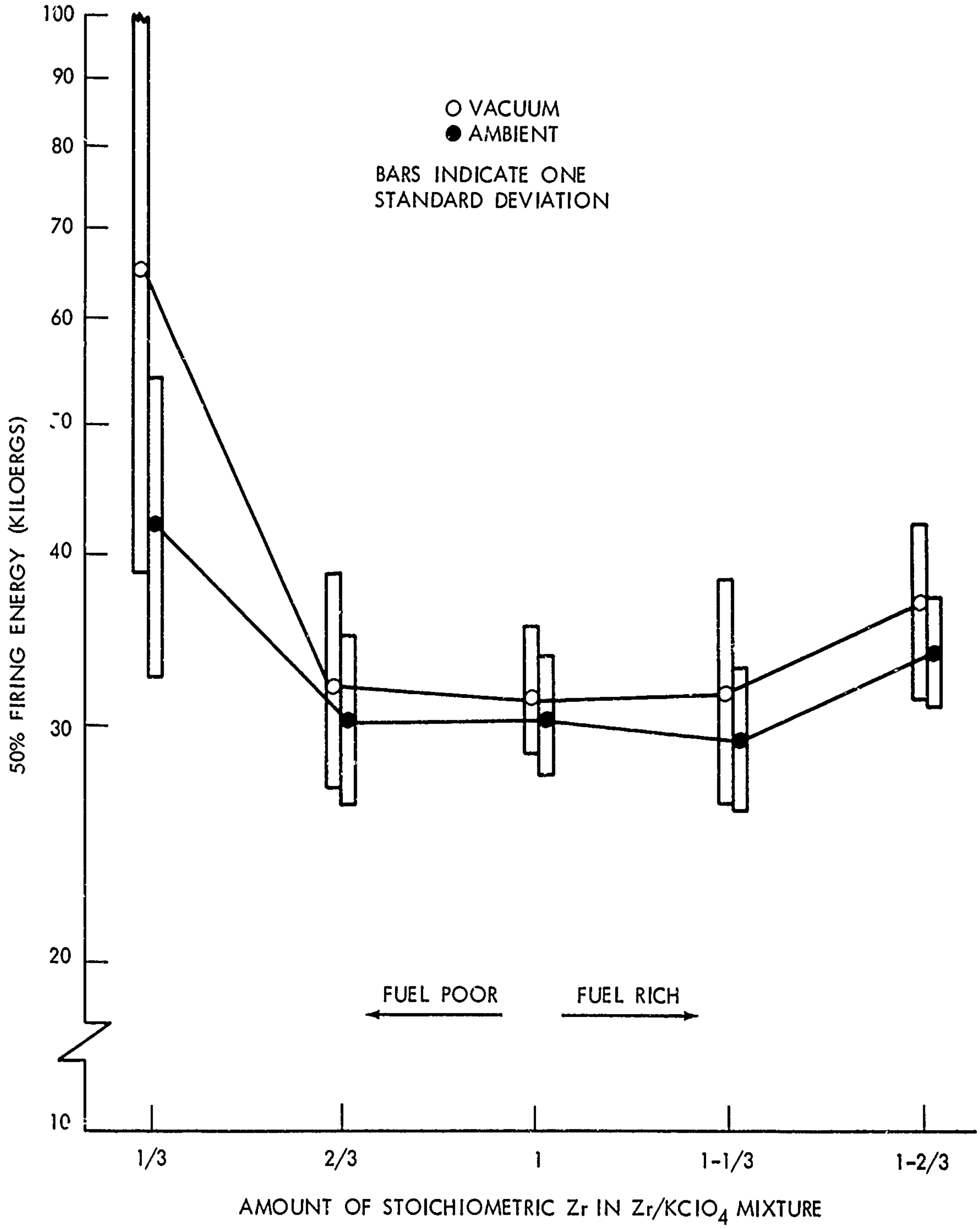

FIG. 4 EFFECT OF VACUUM ON 50% FIRING ENERGY OF Zr/$KClO_4$ MIXTURES

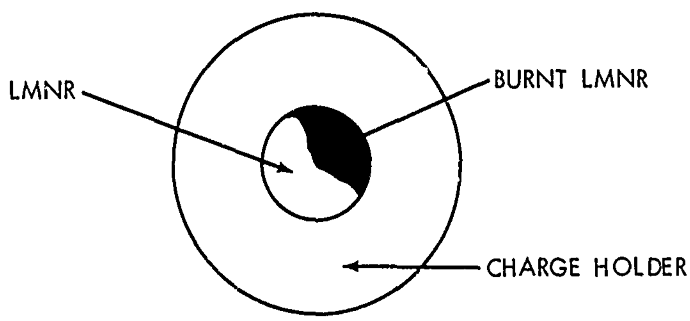

FIG. 5 END VIEW OF CHARGE HOLDER AFTER FIRING

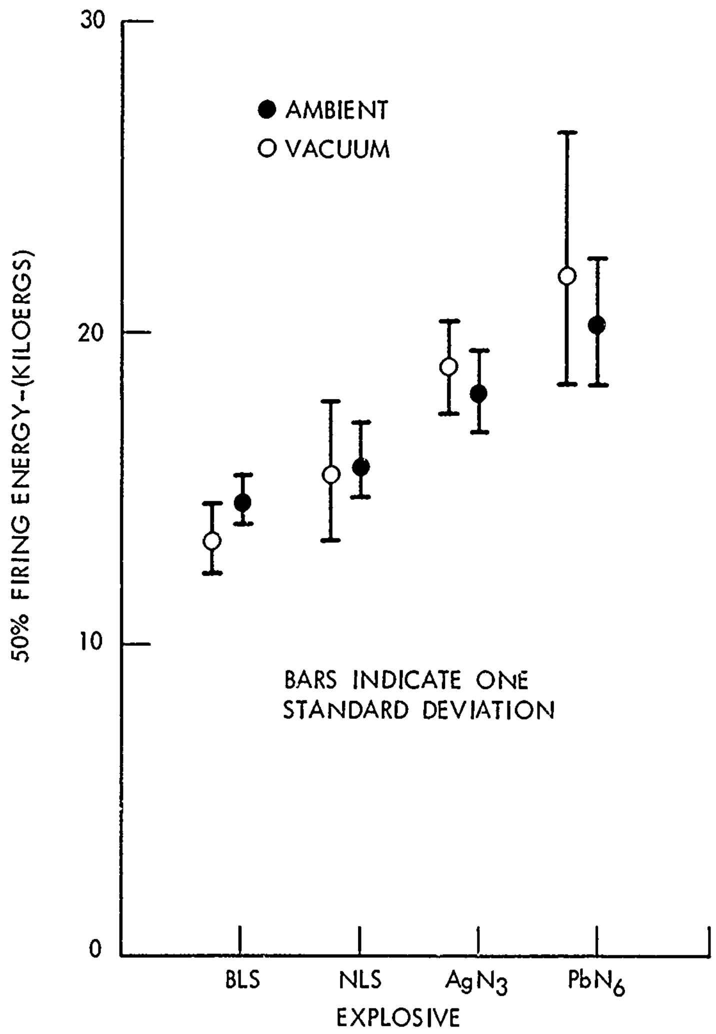

FIG. 6 EFFECT OF VACUUM ON 50% FIRING ENERGY OF PRIMARY EXPLOSIVES

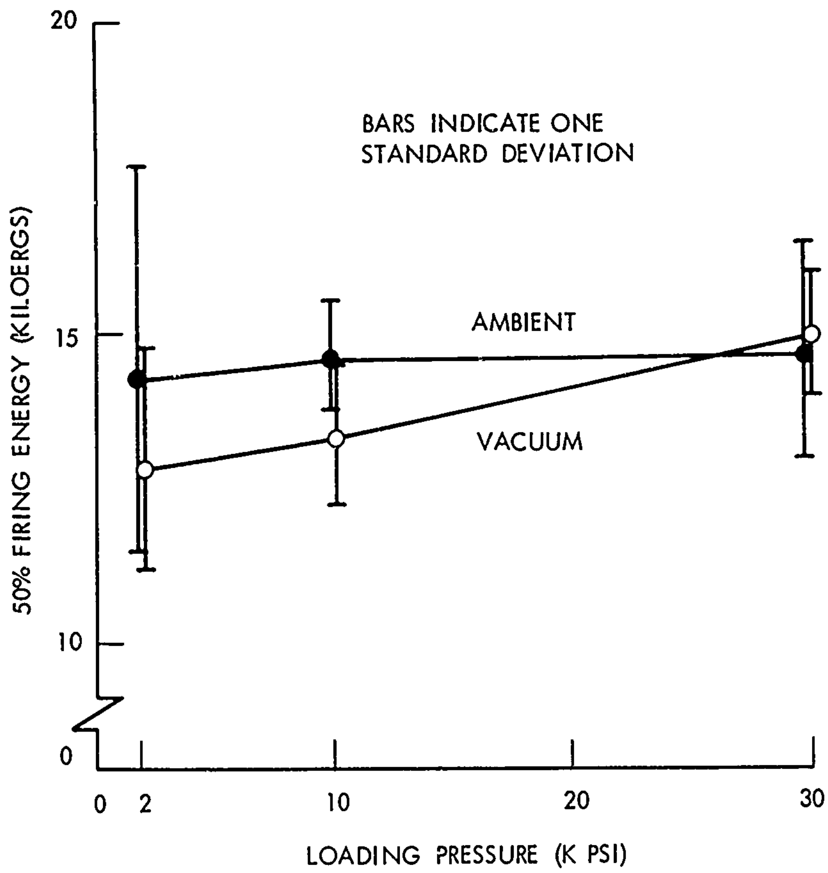

FIG. 7 EFFECT OF LOADING PRESSURE ON 50% FIRING ENERGY OF BASIC LEAD STYPHNATE IN AIR AND VACUUM.

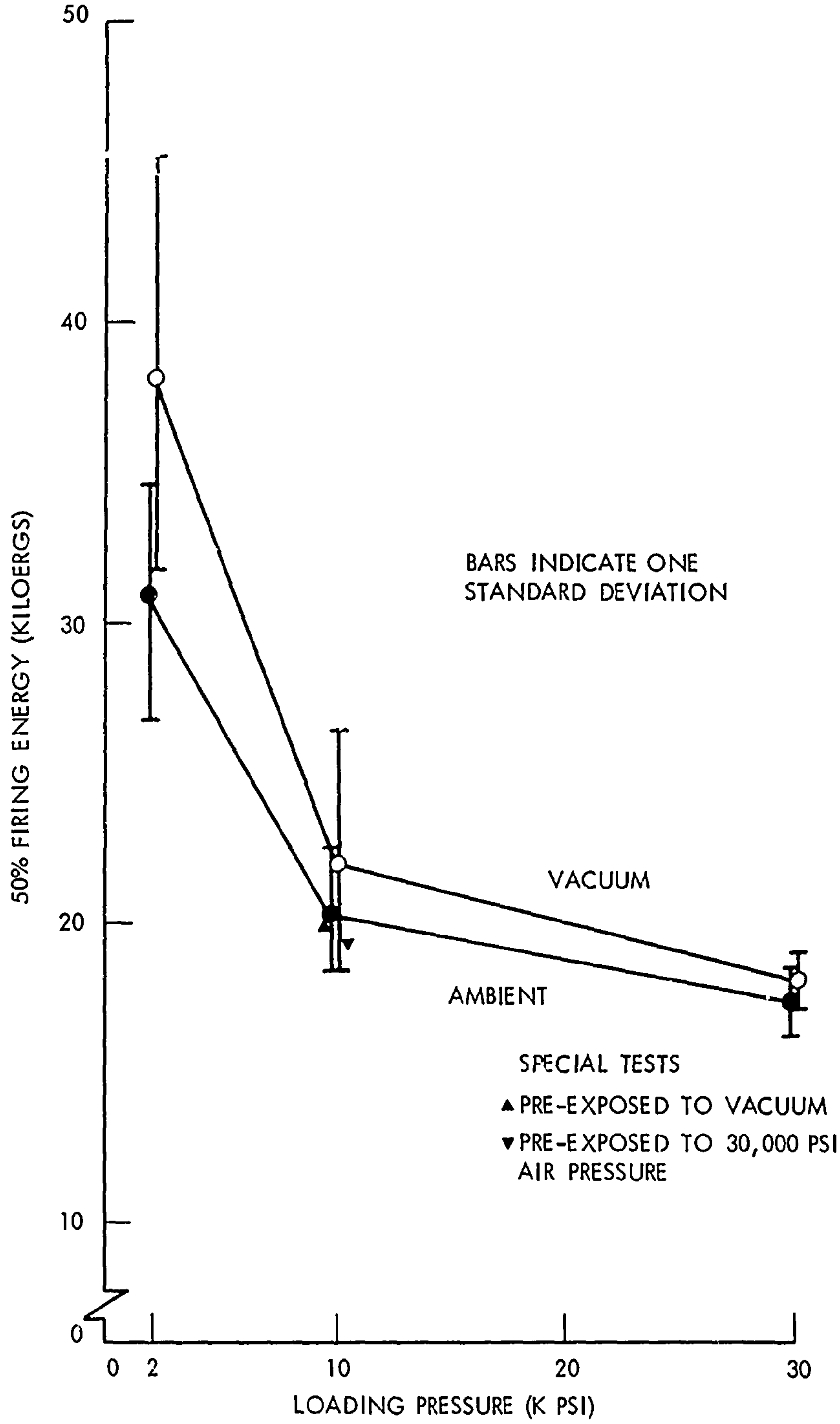

FIG. 8 EFFECT OF LOADING PRESSURE ON 50% FIRING ENERGY OF MILLED DEXTRINATED LEAD AZIDE IN AIR AND VACUUM.

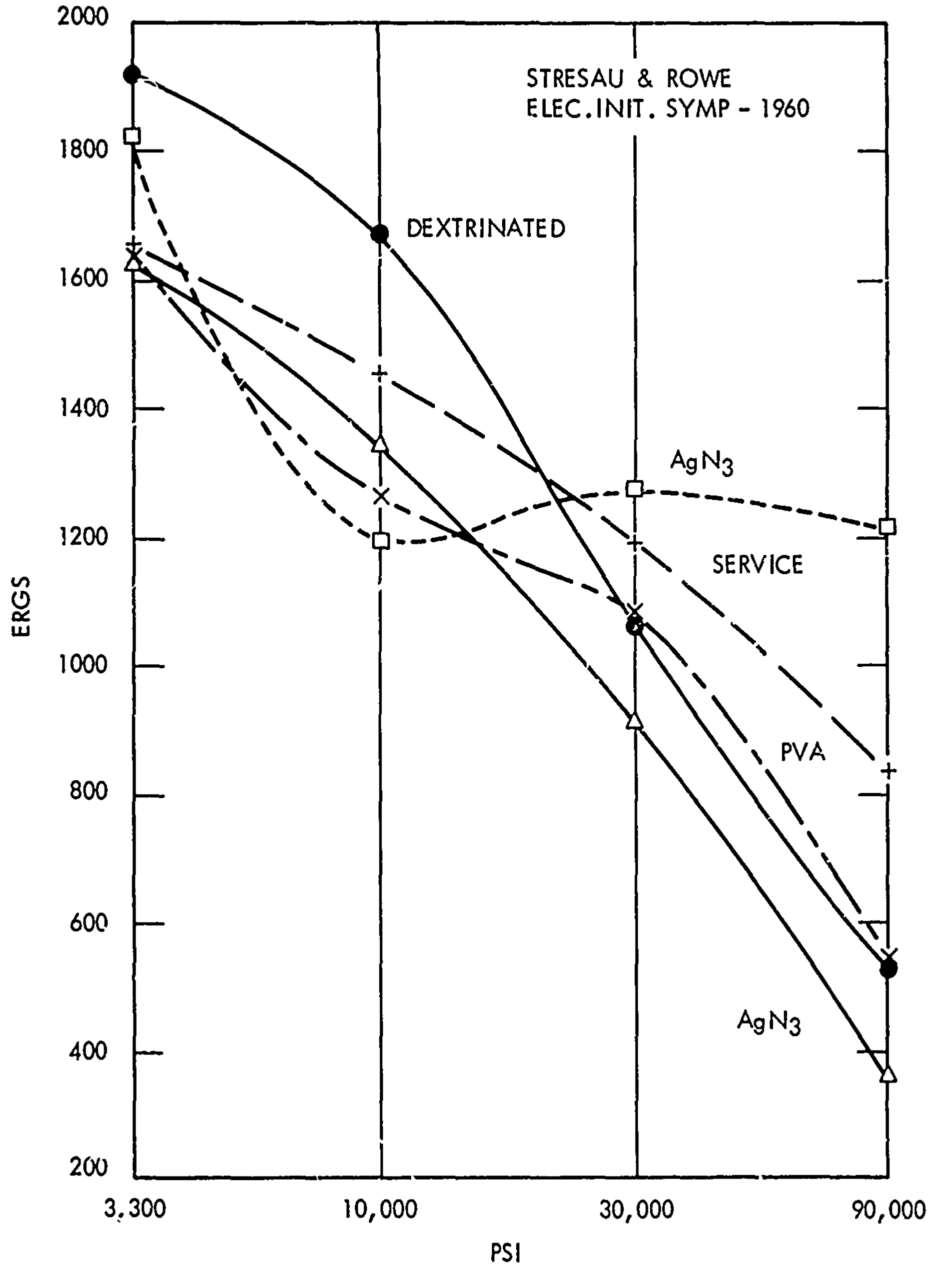

FIG. 9 HOT WIRE SENSITIVITY OF VARIOUS AZIDES

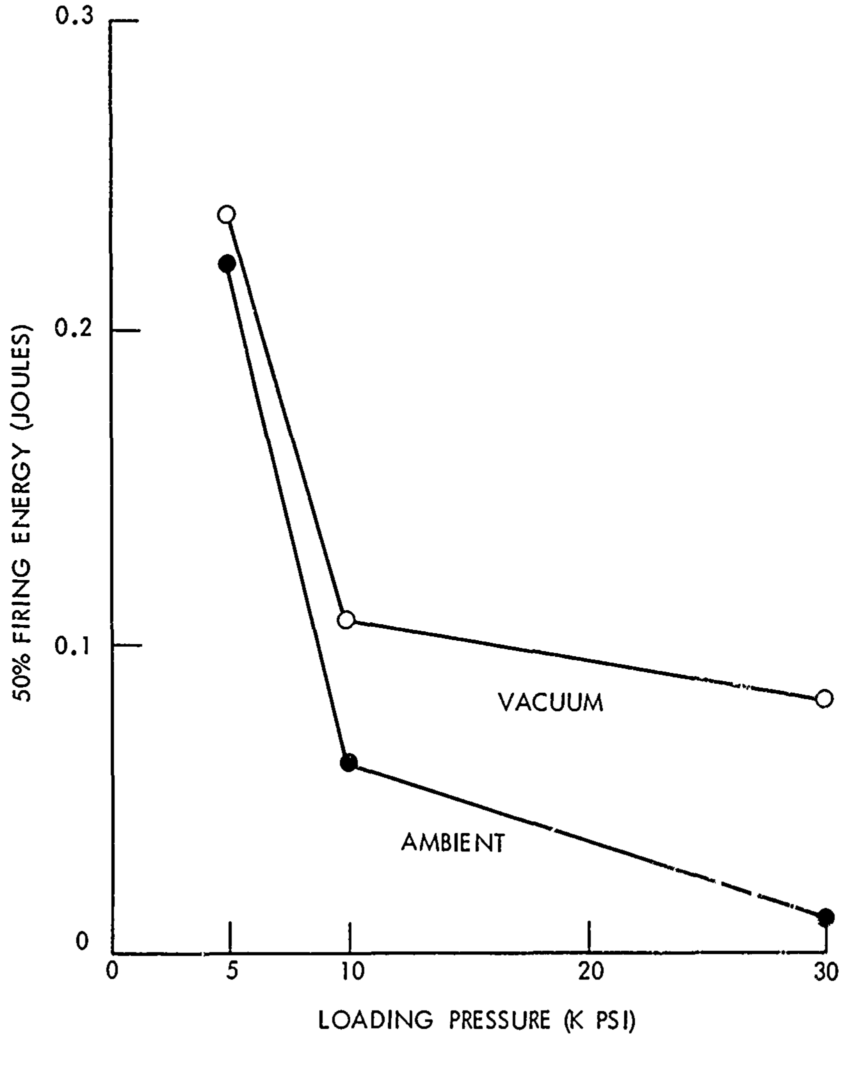

FIG. 10 EFFECT OF LOADING PRESSURE ON 50% FIRING ENERGY OF BLACK POWDER MEAL IN AIR AND VACUUM.

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Security Classification

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Effect of Reduced Ambient Pressure on the Hot Wire Sensitivity of Primary Explosives, Metal-Oxidant Mixtures, and Black Powder

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13. ABSTRACT

The hot wire sensitivity of initiating materials can change under vacuum conditions. Lead azide, silver azide, black powder, and mixtures of $Zr/KClO_4$ require slightly more energy for initiation under vacuum conditions. Basic lead styphnate and normal lead styphnate require slightly less energy for initiation under vacuum conditions. The loading density affects the energy differential. Hypotheses are proposed for the observed energy changes.

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